UNPUBLISHED BY — D.D. Williams Reprint # 593

Introduction

Kalamalka lake is by far the least productive of the mainstem lakes in the Okanagan drainage basin. It also is the only lake that experiences a very active calcium carbonate depositional cycle during the summer stratification season. The relationship between precipitation of calcium carbonate and low productivity has been covered quite extensively in the literature. Ohle (1952) suggested that suspended calcite, as an unuseable form of carbon, reduced photosynthesis in the Grosser Plön er See. Hutchinson (1957, p. 671), however, suggests that much of the colloidal and suspended carbonate observed by Ohle may have been in the form of organic complexes (carbamino carboxylic acid complexes) which are readily useable as a carbon source by algae (Smith et al, 1960). Suspended carbonate effectively adsorbs and complexes certain dissolved organic compounds, thus reducing the direct metabolic utilization of dissolved organics (Wetzel, 1968; 1970; 1972), and complexes and/or sorbs the metallic nutrients, especially iron (Schelske, 1962), as well as some of the macro nutrients such as phosphate (Wetzel, 1965; 1966; Cole et al, 1953), making them physiologically unavailable.

The present discussion does not, however, deal with any specific mechanism by which the lake has managed to remain so unproductive. A study much more detailed in scope than the monitor program completed during the 1971 season would be necessary to make this type of determination. Rather, this portion of the paper is intended to show that sufficient calcium carbonate is precipitated from the trophogenic zone each year to suggest that the ca. annually calcite cycle has probably been an important factor in perpetuating the "unproductive" nature of this lake.

D.D. Williams (unpublished manuscript ~1972) The calcite cycle of Kalamalka L: Influence on lake productivity.

Return to:
Ministry of Environment
Suite 201
3547 Skaha Lake Rd.
Penticton, B.C.
V2A 7K2

Derivation of Carbonate Equilibria

The carbonate cycle was derived from measurements of temperature, pH, calcium and total alkalinity and the effects of changes in these on the equilibrium constants of carbonic acid. Strictly speaking, the values of these thermodynamic constants apply to carbonic acid in distilled water extrapolated to infinitely dilute concentrations, where, theoretically, there are no interactions between ions in solution (i.e. their activity = 1). Extremely dilute aqueous solutions, such as most rivers and lakes, can be considered for all practical purposes to closely approximate this condition. The major dissolved species can be looked upon as individual free ions and a chemical analysis of such waters reported in terms of the major ion content provides a satisfactory model of the internal economy of the solution. In such dilute solutions, where only the long-range electrostatic ionic interactions are of any significance, the activities of the various ionic species (accurate within a few per cent) can be obtained by multiplying the molal species concentration (determined by chemical analysis) by the ion activity coefficients derived from the Debye-Hückel theory. This approximation is fairly reasonable for waters of ionic strength less than 0.1 (Garrels & Christ, 1965). In more concentrated waters, the short-range electrostatic interactions between oppositely charged adjacent ions become increasingly significant (Garrels, Thompson & Siever, 1961) with the result that the effective, free ionic fraction of the ion in question is reduced by the formation of ion pairs.

The ionic strength of Kalamalka Lake water, calculated from the results of lake water analyses ~~done by the Western Water Quality Sub-division, DOE~~ (see Williams, MS 1972) was 0.006. The effects of short-range interactions were, therefore, considered negligible. (Actual determinations by "successive approximations" of the contribution of the ion pairs $CaSO_4^{\,0}$, $CaHCO_3^{\,+}$, and $MgCO_3^{\,0}$, showed that they removed less than 1% of the free ionic fraction of Ca^{2+}, $CO_3^{=}$ and HCO_3^{-} from solution). In consideration of this fact, the values of the activity coefficients for $CO_3^{=}$ (0.73) and HCO_3^{-} (0.94) used in the calculations were those determined by Walker, Bray & Johnson (1927) (see Garrels & Christ, 1965, Fig. 4.5). For similar reasons, the activity coefficient for Ca^{2+} (0.72) was obtained from Garrels & Christ (1965, Fig. 2.15).

The carbonate equilibria were derived from the following relationships as outlined in Garrels & Christ (1965).

$$m_{CO_3^=} = \frac{m_{HCO_3^-} \cdot \gamma_{HCO_3^-} \cdot K_{HCO_3^-}}{a_{H^+} \cdot \gamma_{CO_3^=}} \qquad (1\ )$$

$$m_{Ca^{2+}} = \frac{K_{CaCO_3}}{m_{CO_3^=} \cdot \gamma_{Ca^{2+}} \cdot \gamma_{CO_3^=}} \qquad (2\ )$$

$$m_{CO_{2(aq)}} = \frac{m_{HCO_3^-} \cdot \gamma_{HCO_3^-} \cdot a_{H^+}}{K_{H_2CO_3}} \qquad (3\ )$$

$$\Sigma m_{CO_2} = \Sigma m_{HCO_3^-} + \Sigma m_{CO_3^=} + m_{CO_{2(aq)}} \qquad (4\ )$$

$$IAP = a_{Ca^{2+}} \cdot a_{CO_3^=} \qquad (5\ )$$

The molal concentration of $CO_3^=$ ($m_{CO_3^=}$) was calculated from the analytical bicarbonate concentration, pH and the $K_{HCO_3^-}$ value at the <u>in situ</u> temperature extrapolated from the values determined by Harned and Scholes (1941). This was used in (2), to calculate from the solubility product relationship, the concentration of dissolved calcium for comparison with the analytical value of the calcium concentration as an indication of how much $CaCO_3$ might be in the colloidal or suspended form. It essentially indicates the degree of saturation of the water with respect to $CaCO_3$, similar to (5). Values for K_{CaCO_3} at the <u>in situ</u> temperatures were extrapolated from those determined by Larson & Buswell (1942). This value for $m_{CO_3^=}$ was also used in the determination of the total CO_2 content of the water (4), and in the calculation of the IAP (ion activity product) in (5).

Using the values from Harned & Bonner (1945) for $K_{H_2CO_3}$ for the <u>in situ</u> temperature, the dissolved CO_2 ($m_{CO_{2(aq)}}$) fraction ($\approx m_{H_2CO_3}$) of the total CO_2 content of the water was calculated.

Finally, using the calculated value for $m_{CO_3^=}$ (1) and the analytical value for the calcium concentration ($\Sigma m_{Ca}2+$), the ion activity product was determined for comparison with the equilibrium constant for calcite (K_{CaCO_3}) at the *in situ* temperature (Berner, 1965). This ratio, IAP:K_{CaCO_3}, gives an estimate of the degree of saturation of calcite in the water column, (i.e. IAP:$K_{CaCO_3} < 1$, the sample is undersaturated; IAP:$K_{CaCO_3} = 1$, the sample is saturated; IAP:$K_{CaCO_3} > 1$, the sample is supersaturated).

Several different approaches were attempted in calculating the quantity of calcium carbonate (calcite) precipitated from the lake each year. In each case, the calculations were limited to the 0 - 10 m volume, i.e. that amount of calcite precipitated through the 10 m contour.

A plot of the seasonal changes in the IAP:K_e ratio vs depth (Fig. 19), indicated that the calcite precipitated from the upper layers of the lake (epilimnion) was being re-dissolved in the hypolimnion. The sediment data corroborated this fact, with the calcium carbonate content of the sediments being approximately inversely proportional to water depth (St. John, ~~MS~~ unpublished 1972) (Fig. 17). The terrace deposits were composed almost entirely of calcite (85-90%), whereas the carbonate content of the deeper basin muds was only 10%. This would indicate the epilimnion to be the crystal generating source for the microcrystalline calcium carbonate. ~~Both these~~ Similar observations ~~are supported by the work of~~ have been made by Brunskill (1969) and Takahashi et al (1968) on meromictic, Fayettville Green Lake, N.Y., which also actively precipitates calcium carbonate. Brunskill (1969) observed that crystals recovered from the surface waters tended to be sharply angled, whereas those from the deeper waters tended to be more stubby and rounded, suggesting that some re-solution was ~~possibly~~ occuring. Takahashi et al ( ) showed that the ^{13}C content of the surface sediments of the deep basin of the lake could be correlated with the dissolved, inorganic $^{13}CO_2$ of the surface water and was entirely different from that of the monimolimnion. Confining calculations to the volume above the 10 m contour has, hopefully, eliminated the complications introduced as a result of this re-solution process in the deeper waters.

From the work of Kemp and St. John (St. John, unpubl ~~MS 1972~~) and Anderson (1972), excellent geochemical data exist for the terrace sediments. These data, in the absence of any direct measurements of the suspended crystal loads in the water column, permit a semi-empirical determination to be made of the quantity of calcite precipitated from the epilimnion each year, since the mean depth of the terraces (~10 m), approximates the mean depth of the thermocline over the summer stratification season.

The very unproductive nature of this lake has been well documented in works by Stockner et al. (~~MS~~ 1972) and ~~the present author~~ (Williams, ~~MS~~ 1972). In order to determine if the calcium carbonate cycle has been a major factor in "protecting" the lake from water quality deterioration since man settled in the Valley, as suggested by St. John (~~MS 1972~~), it is first necessary to determine the amount of calcium carbonate being precipitated each year. If indeed, complexing, sorption or co-precipitation phenomena are occurring as a result of calcite precipitation, thus

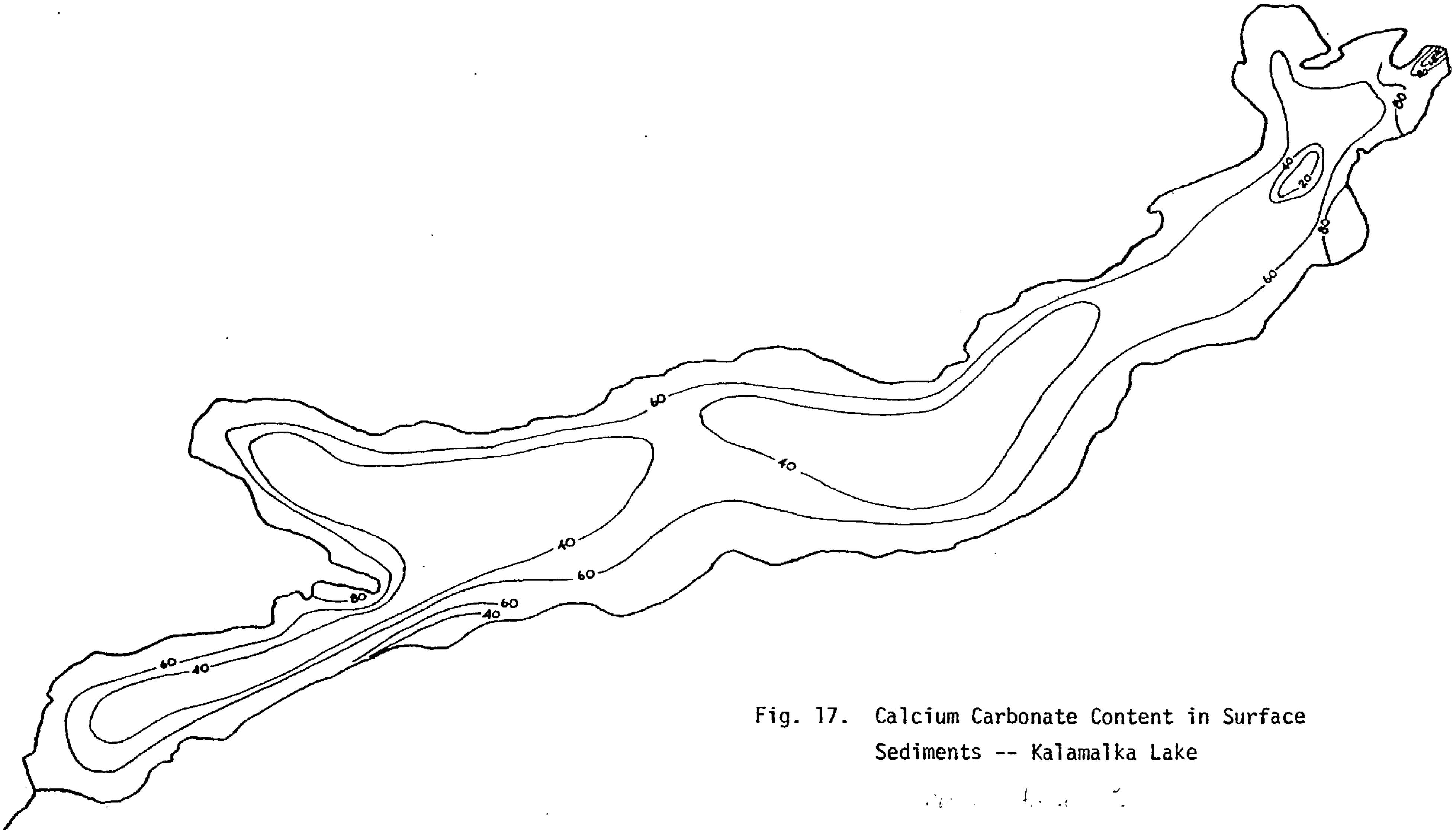


Fig. 17. Calcium Carbonate Content in Surface Sediments -- Kalamalka Lake

data from St. John (MS 1972)

decreasing the availability of organics, or such species as phosphate or iron to the algal community of the lake, the region of greatest importance insofar as the precipitation of calcite is concerned becomes the trophogenic zone, which can be approximated roughly by the surface 10 m.

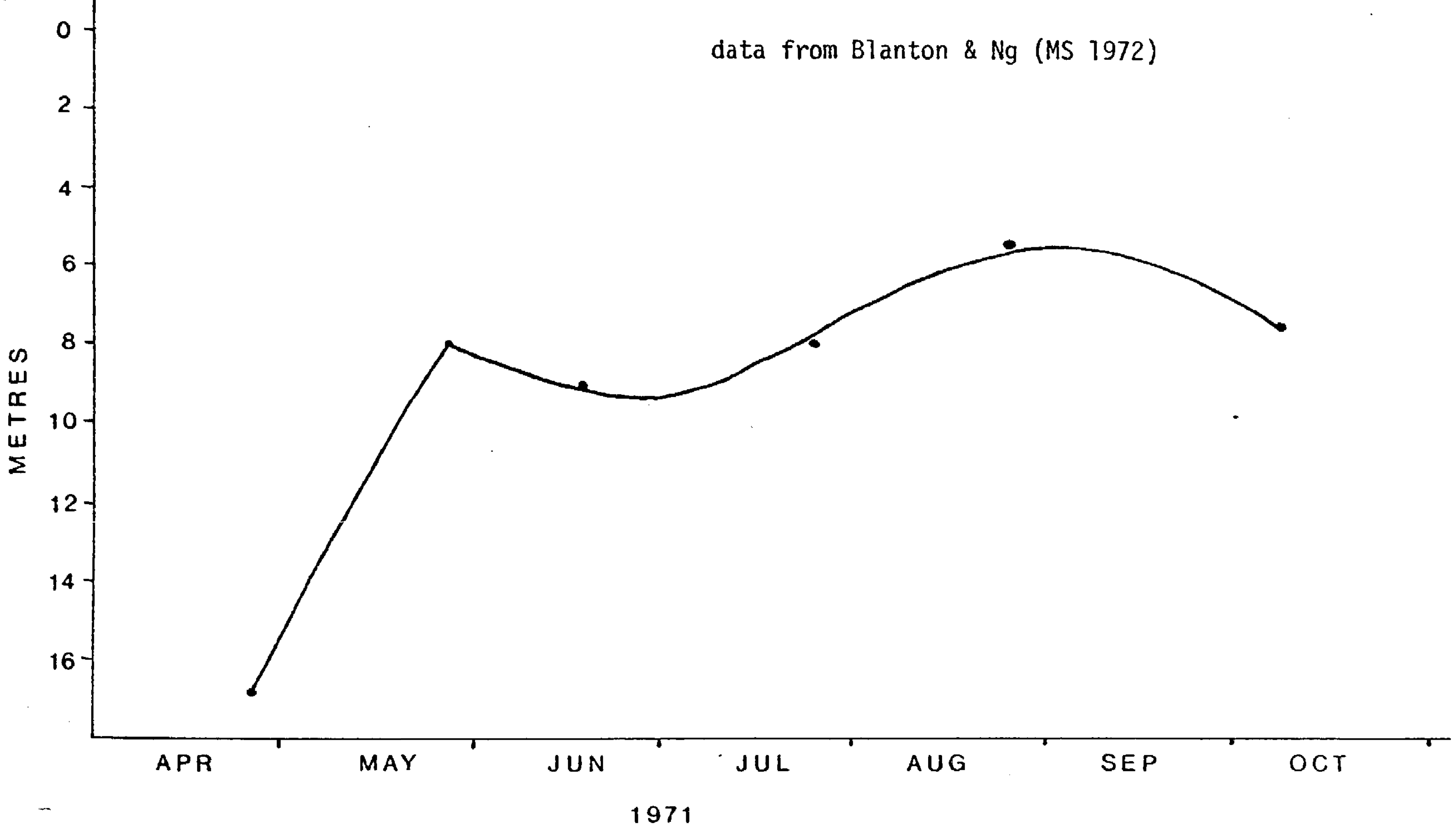
The Precipitated Crystals

A drastic change in Secchi depth from 17 to 7 metres (Fig. 18) as well as a change in lake water appearance from dark blue to almost opalescent white in May, readily indicates the onset of crystal precipitation. Although no direct collection of suspended crystals from the water column was made, they were readily detected during the summer as precipitates on the casings of thermographs moored in the lake at a depth of 3 m (Blanton & Ng, ~~MS~~ 1972), and on the glass slides of periphyton moorings at a depth of 2 m (Stockner, ~~MS~~ 1972).

Crystals from Shipek and core samples taken of the terrace sediments were identified by micro-electron diffraction analysis as calcite, with hexagonal crystal structure and a size range of 0.5 to 5µ (Durham, personal communication ~~Radiochemistry Unit, CCIW~~). Their morphological features, examined under a scanning electron microscope ~~(University of Toronto),~~ indicated formation by nucleation processes at an original crystal surface and by dendritic growth with preferred orientations. Crystal aggregates were also observed.

These data agree reasonably well with the observations made by Brunskill (1969) on Fayettville Green Lake. Measurements of crystals collected directly from the water column using sediment traps, and crystals from the sediment laminae, resulted in a mean nominal radius of 3µ, which closely approximates the crystal sizes observed in Kalamalka Lake. Crystal aggregates with diameters up to 60µ were also observed.

Fig. 18. Lake Mean Secchi Depth, 1971 -- Kalamalka Lake



data from Blanton & Ng (MS 1972)

Water Chemistry Data

The change in total CO_2 observed in the lake during the 1971 season is plotted in Fig. 20, indicating a decrease of approximately $0.18 \times 10^{-3} \Sigma m_{CO_2}$ from April through October (largely as a result of a decrease in $\Sigma m_{HCO_3^-}$). The effect was essentially limited to the surface 15 metres of the lake and agrees reasonably well with the seasonal distribution of temperature (Fig. 21). According to the equation,

$$Ca^{2+} + 2HCO_3^- \rightleftharpoons CaCO_3\downarrow + CO_2\uparrow + H_2O \qquad (6)$$

a decrease of 0.18×10^{-3} $m_{HCO_3^-}$ requires the precipitation of 0.09×10^{-3} $m_{CaCO_3^\circ}$ and the evolution of 0.09×10^{-3} m_{CO_2} either to the atmosphere or to be taken up by algae.

Calculated for the 0-10 metre volume of the lake (volume = 0.24×10^9 m^3), this would result in the precipitation of 2.16×10^9 g $CaCO_3$, assuming no solution of the crystals or loss to outflow.

The net change in the CO_2 system also requires a decrease of 0.11×10^{-3} $m_{Ca^{2+}}$ or the equivalent of 2.16×10^7 moles Ca^{2+} in the 0-10 m volume. A rough calcium budget worked out for the lake resulted in a loss of approximately 2.0×10^7 moles Ca^{2+} (Williams, unpublished data). The two estimates correspond extremely well.

Fig. 19 indicates a threefold increase in the apparent degree of supersaturation with respect to calcite of the surface few metres of the lake from June to September, with the maximum values occurring in August. In general, the isopleths follow the descent of the thermocline. Vertical cooling curves start appearing in late September (Fig. 21), and as the surface water cools, the saturation values start decreasing. In all probability, the lake fluctuates slightly around the saturation level during the winter months.

The increased saturation values can be almost entirely attributed to the changes in $a_{CO_3^=}$, which increased more than twofold from 1.15×10^{-5} in April to 2.60×10^{-5} in August, largely as the result of the effect of temperature on the equilibrium constant for HCO_3^-. m_{CO_2} also decreased in the surface waters over this period, from 6.00×10^{-5} to 2.80×10^{-5} m_{CO_2}. Removal of dissolved CO_2 increases the pH and thus favours the precipitation of $CaCO_3$.

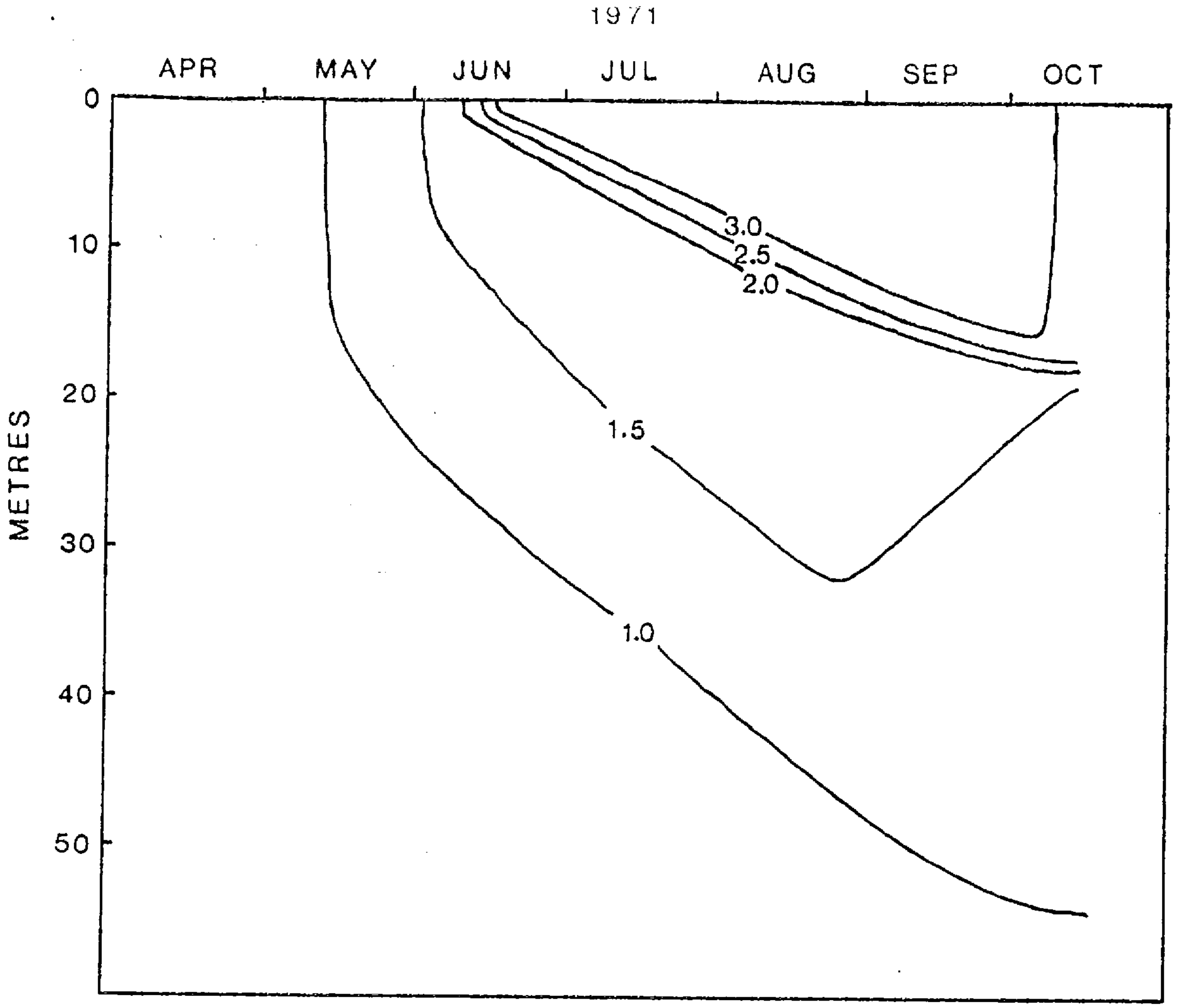


Fig. 19. Seasonal changes in the IAP:K_{CaCO_3} Ratios, 1971 -- Kalamalka Lake

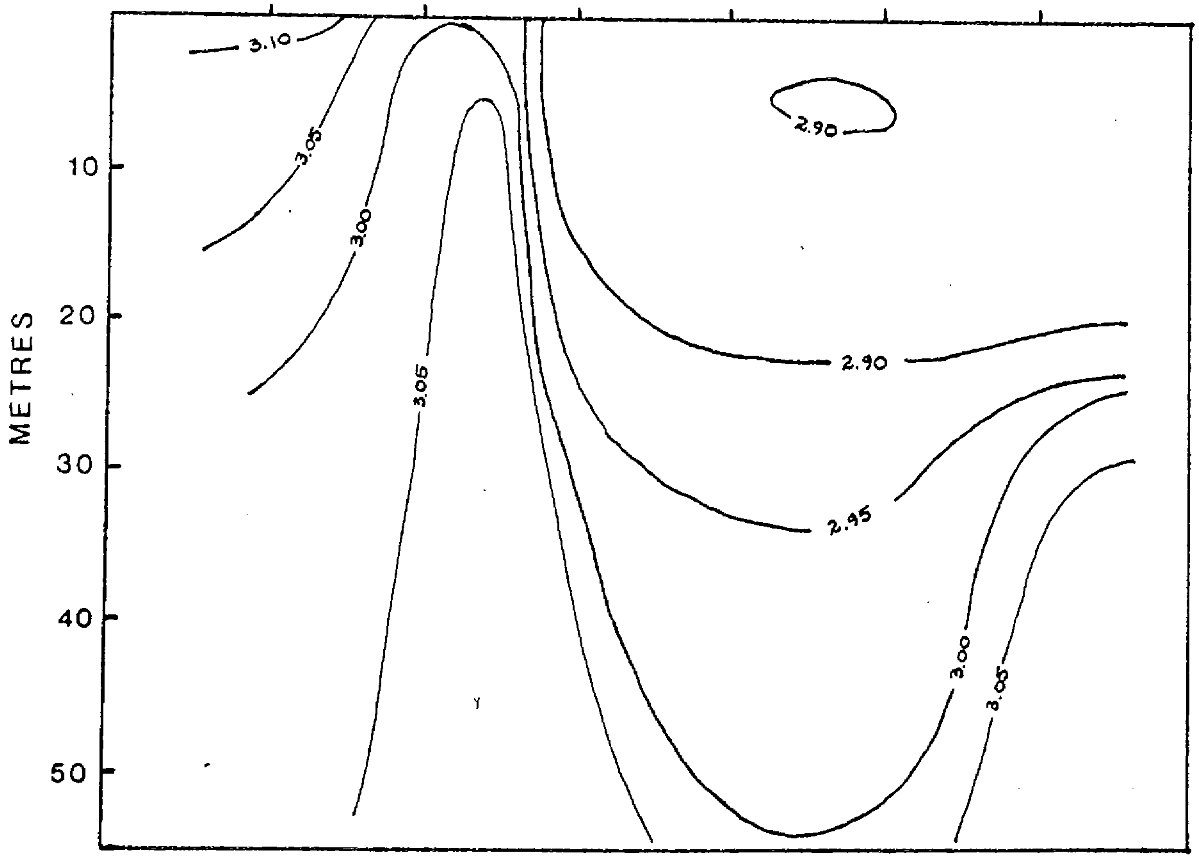


Fig. 20. Seasonal Distribution of ΣCO_2 (moles/litre x 10^{-3})

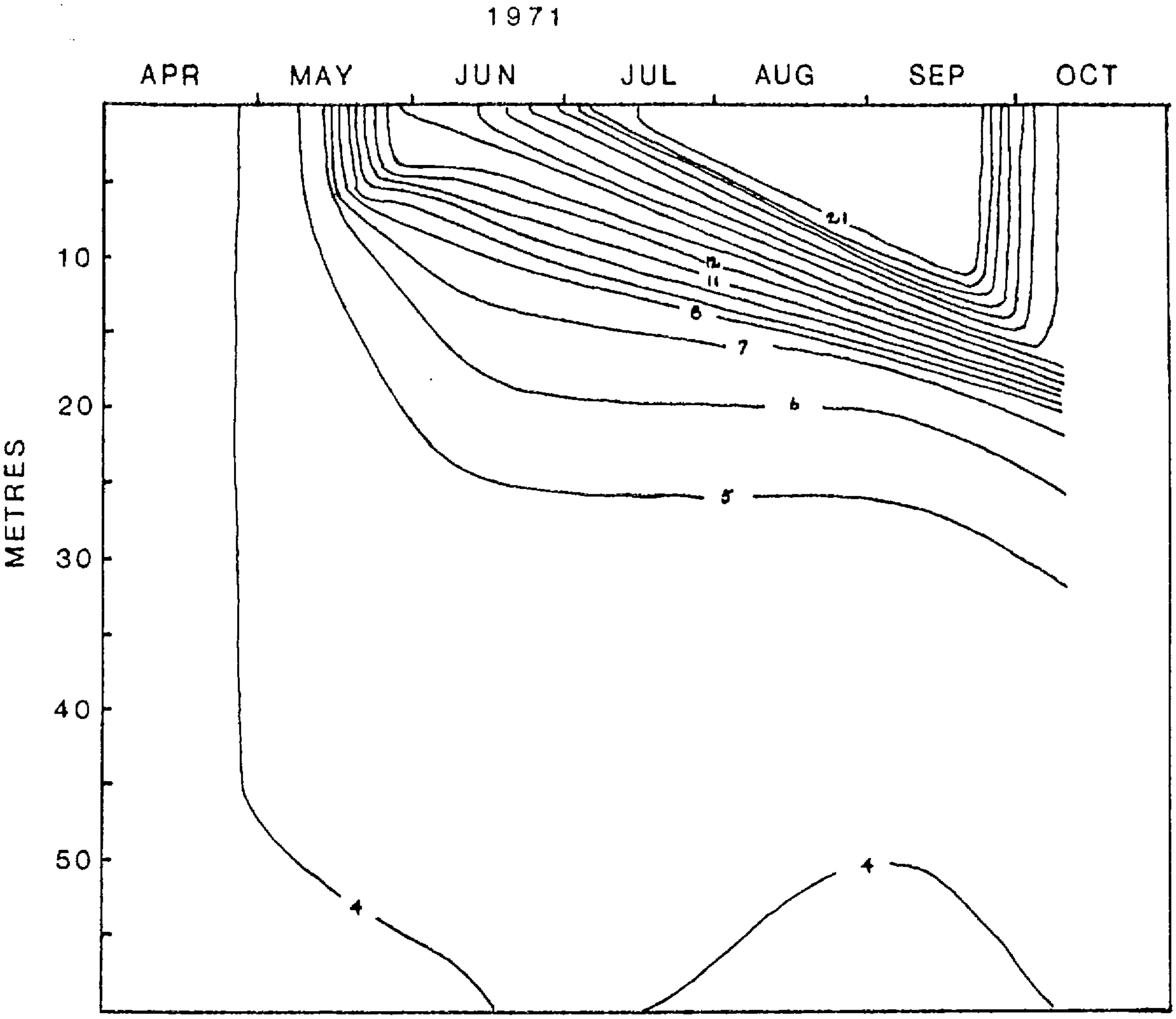


Fig. 21. Seasonal Temperature Isopleths -- Kalamalka Lake

Sediment Data

An attempt was made to correlate the results from the water chemistry analyses with the sediment data collected by Anderson, Kemp and St. John (St. John, ~~MS~~ 1972; Anderson, ~~MS~~ 1972).

Using sediment densities from Anderson (~~MS~~ 1972) and mean water content for the uppermost sediment column (Kemp, unpublished data), the mean net annual accumulation of sediment (dry weight) for the lake was calculated by St. John as 413 g/m^2 lake surface/yr. This is equivalent to a sedimentation rate through the 10 m contour (area = 23 x 10^6 m^2) (in St. John 1972) of 9.5 x 10^9 g/yr.

Kemp has determined a mean inorganic carbon content for the terrace sediments of 10.2% by weight ~~(see St. John, MS 1972)~~. Using the total sedimentation rate calculated above, this is equivalent to 9.69 x 10^8 g (8.08 x 10^7 moles) inorganic carbon being deposited through the 10 m contour each year. If it is assumed that all this were in the form of calcium carbonate, then the total amount of calcite sedimented from the 0 - 10 m volume amounts to 8.08 x 10^9 g/yr. About 10% of this is of terrigenous origin (St. John, MS 1972) which results in 7.3 x 10^9 g being precipitated from the water in the lake.

St. John (op. cit) has determined a mean Ca^{2+} content for the terrace sediments (as CaO) of 49.8% by weight. Using similar considerations as above for inorganic carbon, the calculations result in 8.45 x 10^9 g $CaCO_3$ being precipitated through the 10 m contour. Allowing for the 10% terrigenous fraction, results in 7.6 x 10^9 g/yr originating from the water column. The two results show strikingly good agreement, suggesting that the assumption made above was probably quite valid. The slight discrepancy that does exist could readily be attributed to sample variability and/or differences produced by the analytical methods used for measuring the two parameters.

Considering that the water chemistry data are based on only one year's observation (April to October), whereas the sediment data are based on the mean of a hundred years' accumulation of sediment, the correlation between the two sets of results is also quite reasonable. The apparently higher sedimentation rate for calcite obtained from the sediment data (7.5 x 10^9 g/yr) as compared to that obtained from the water chemistry (2.2 x 10^9 g/yr) could also be attributed to the fact that a total sedimentation rate based on the results for the deeper basin muds was used for the calculations. Considering the morphometry of this lake, it is questionable (in the author's opinion) whether this value can be validly extrapolated over the entire surface.

Fig. 19 indicates that the water is still supersaturated with respect to calcite in October. The fraction of this suspended calcite that would probably be precipitated from the water column before the surface waters return to saturation, was not included in the calculations. This would obviously tend to increase the sedimentation rate obtained from the water chemistry data.

It is probable that most of the calcium carbonate precipitated from this lake originates by inorganic, as opposed to biogenic processes, with the main initiating (and terminating) factor being the effect of temperature on the equilibria constants for carbonic acid and the activity product constant for $CaCO_3$. Photosynthesis probably functions only in a minor secondary role.

The onset of crystal precipitation in late May, as evidenced by the change in both Secchi depth and water appearance, coincides with the beginning of stratification and formation of the thermocline. Epilimnion heating rates in the order of 250-350 g.cal/cm^2/da persist throughout the period April to mid-June (Blanton & Ng, ~~MS~~ 1972). The IAP:K_{CaCO_3} ratio increases throughout the summer, with the isopleths generally following the descent of the thermocline. Total dissolved CO_2 starts decreasing in mid-May. The high values for IAP:K_{CaCO_3} which persist throughout the stratification period may indicate that the surface waters were being constantly replenished with CO_2 (perhaps by mixing and warming of water in the thermocline, see Brunskill, 1969). It may also indicate that the turbulence in the epilimnion was tending to keep the crystals in suspension. This would also explain, in part, the relatively lower value for calcite precipitation calculated from water chemistry data (April - October) as opposed to the value obtained from sediment data.

Although no direct studies were made to determine if the very unproductive nature of Kalamalka Lake could be linked with the active calcium carbonate cycle, the calculations show that the quantity of calcite precipitated from the trophogenic region each year is sufficient enough to suggest, at least, that it could be acting as a "protective mechanism" in this lake.

Crystal Settling Velocities

Although it was considered unreasonable to assume that crystal sedimentation rates based on Stokes' Law could be calculated for the region of the lake above the thermocline, it was thought that such would not be the case for the hypolimnion. This region of the lake does not experience the turbulence of the epilimnion, which would, in general, tend to keep the crystals in suspension. In addition, any error associated with the effect of changing temperature on water viscosity (which can be quite considerable, [illegible] is drastically reduced by the isothermal nature of the hypolimnion.

The effect of temperature on the carbonate equilibria constants appears to be the initiating factor for calcite precipitation in this lake (see discussion below). Since the temperature fluctuations below 25 m were virtually negligible (Fig. 21), it was assumed that the apparent supersaturation of calcite in the hypolimnion below this depth was the result of precipitation from the layers of the lake above. Consequently, the rate of descent of the IAP:K_e = 1.5 isopleth was used as being representative of the "settling velocity" of the calcite crystals. This resulted in a value of 2.89×10^{-4} cm/sec. Substituting this value into the Stokes' equation,

$$v = \frac{2}{9} \frac{(\rho_1 - \rho_2) g r^2}{\eta} \qquad (7)$$

where, ρ_1 = density of calcite (2.71 g/cm^3)
ρ_2 = density of lake water (1.00 g/cm^3)
g = acceleration due to gravity (980 cm/sec^2)
v = particle settling velocity (2.89×10^{-4} cm/sec)
η = viscosity of water (0.016 at 4.5°C) (g/cm.sec) = 1 poise
r = particle radius

resulted in a particle size of approximately ~~2~~ 1.1μ. This is ~~in the middle of~~ at least within the crystal size range determined by electron diffraction.

It would be interesting to compare the approximated settling velocity with that observed using actual crystals collected from the water column and settling tube techniques.

REFERENCES

Anderson, T.W. 1972. Historical evidence of land use in pollen stratigraphies from Okanagan mainstem lakes, B.C. (in preparation)

B.C. Pollution Control Branch, Victoria. 1971. Calculations of Nutrient loadings by streams. Weekly data for the period Aug 1969-Jul 1970. (computer printout).

____________________. 1971. Monthly and annual summary of loadings by streams and outfalls for the period Aug 1969-Jul 1970. (computer printout).

____________________. 1972. Calculations of Nutrient loadings by streams. Weekly data for the period Aug 1970-Jul 1971. (computer printout).

____________________. 1972. Monthly and annual summary of loadings by streams and outfalls for the period Aug 1970-Jul 1971. (computer printout).

Berner, R.A. 1965. Activity coefficients of bicarbonate, carbonate and calcium in sea water. Geochem. Cosmochim. Acta, 29: 947-965.

Blanton, J.O., and A.R. Winklhoffer. 1971. Physical processes affecting the hypolimnion of the Central Basin of Lake Erie. <u>in</u>: Project Hypo. CCIW Special Paper No. 6. pp 9-38.

* __________, and H.Y.F. Ng. 1972. The physical limnology of the mainstem lakes in the Okanagan Basin, B.C. (Vol. I: Results). MS Report, Canada Centre for Inland Waters, 34p plus Figs.

__________. 1972a. Vertical entrainment in stratified lakes. (unpublished MS) p. 11.

__________. 1972b. Some comparisons in the thermal structure of five lakes in the Okanagan Basin, British Columbia. (in press for publication in J. Fish. Res. Bd. Can.).

Brunskill, G.J. 1969. Fayettville Green Lake, N.Y. II: Precipitation and sedimentation of calcite in a meromictic lake with laminated sediments. Limnol. Oceanogr., 14: 830-848.

Burns, N.M., and C. Ross. 1972. Oxygen-nutrient relationships within the Central Basin of Lake Erie. <u>In</u>: Project Hypo. CCIW Special Paper No. 6. pp. 85-119.

Cole, C.V., S.R. Olsen, and C.O. Scott. 1953. The nature of phosphate sorption by Calcium carbonate. Soil Sc. Soc. Amer. Proc., 17: 352-356.

Garrels, R.M., C.L. Christ, and R. Siever. 1961. Control of carbonate solubility by carbonate complexes. Am. J. Sci., 259: 24-25.

__________, ________. 1965. Solutions, minerals and equilibria. Harper & Row, N.Y. 450p.

Harned, H.S., and S.R. Scholes. 1941. The ionization constant of HCO_3 from 0-50°C. J. Am. Chem. Soc., 63: 1706-1709.

__________, and F.T. Bonner. 1945. The first ionization constant of carbonic acid in aqueous solution of sodium chloride. J. Am. Chem. Soc., 67: 1026-1031.

Hutchinson, G.E. 1938. On the relation between the oxygen deficit and the productivity and typology of lakes. Int. Rev. Hydrobiol., 36: 336-355.

______________. 1957. A Treatise on Limnology. Vol. I: Geography, Physics and Chemistry. John Wiley & Sons, N.Y. 1015p.

* Kennedy, G. 1972. Interim estimate of nutrient contribution to receiving waters from agricultural sources via groundwater transport. MS Report. Faculty of Applied Science, Univ. of British Columbia, p. 28.

Larson, T.E., and A.M. Buswell. 1942.

* LeBreton, E.G. 1972. Cleaning, development, test pumping and instrumentation of test holes drilled under Task No. 40 and completed for observation well purposes. MS Report. BCWIB. Dept. of Lands, Forests and Water Resources, Victoria, B.C., p. 26.

* Lerman, A. 1972. Final Report on the chemical limnology of the major lakes in the Okanagan Basin: Nutrient budgets at present and in the future. MS Report. Canada Centre for Inland Waters, 33p plus Figs.

Ohle, W. 1952. Die hypolimnetische Kohlendioxyde-Akkumulation als productionsbiologischer Indicator. Arch. Hydrobiol., 46: 153-285.

Rawson, D.S. 1939. Physical and chemical studies, plankton and bottom fauna of Okanagan Lake, B.C., in 1935 with appended data from adjacent smaller lakes. Bull. Fish. Res. Bd. Can., 56: 3-26.

Robertson, S. 1972.

* Sandve, G.P. (comp.). 1971. An economic study of the Okanagan-Shuswap Region. MS Report. Economics and Statistics Branch, Dept. of Industrial Development, Trade and Commerce, Victoria, B.C. 150p plus Appendices

Schelske, C.L. 1962. Fe, organic metter and other factors limiting productivity in a marl lake. Science, 136: 45-46.

Slezak, M.W. 1971. Water quality and septic tank research data. MS Report. British Columbia Pollution Control Branch, Victoria, B.C., 2p.

Smith, J.B., M. Tatsumoto, and D.W. Wood. 1960. Carbamino-carboxylic acids in photosynthesis. Limnol. Oceanogr., 5: 425-431.

* St. John, B.E. 1972. The limnogeology of the Okanagan mainstem lakes. MS Report. Canada Centre for Inland Waters, p.46 plus data.

* Stockner, J.G.

* Stockner, J.G., G.R. Girman, and R.D. Robarts. 1972. Algal nutient addition and pure culture bioassay studies on six lakes in the Okanagan Basin, British Columbia. MS Report. Fish. Res. Bd. Can., Freshwater Institute, p.52 plus Figs.

* ____________. 1973. Appendix 5 to the summary of the annual report of the Okanagan Basin Study Committee. Canada-British Columbia Okanagan Basin Agreement,

Takahashi, T., W.S. Broecker, Y.H Li, and D. Thurber. 1968. Chemical and isotopic balances for a meromictic lake. Limnol. Oceanogr., 13: 272-292.

Thienemann, A. 1928. Der Sauerstoff im eutrophen und oligotrophen Seen. Die Binnengewässer, 4. Stuttgart, Schweizerbartsche Verlagsbuchhandlung, 175p.

* Thomson, A.M. (comp.). 1971. Summary report on Ellison-Wood-Kalamalka Sub-Basin. Canada-British Columbia Okanagan Basin Study Committee. MS Report, p.5 plus data.

Todd, D.K. 1959. Groundwater Hydrology. John Wiley & Sons, N.Y.

Traversy, W.J. 1971. Methods for chemical analysis of waters and wastewaters. Water Quality Division, Inland Waters Branch, Ottawa.

Vollenweider, R.A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with prticular reference to nitrogen and phosphorus as factors in eutrophication. O.E.C.D., Paris, p.135.

_______________. 1969. Möglichkeiten und Grenzen elementarer Modelle der Stoffbilanz von Seen. Arch. Hydrobiol., 66: 1-36.

Water Survey of Canada. 1970. Surface Water Data, British Columbia. Inland Waters Branch, DOE, Ottawa.

___________________. 1971. Surface Water Data, British Columbia, Inland Waters Branch, DOE, Ottawa.

West Water Quality Sub-Division. 1972. Okanagan Pollution Survey, Full Analyses, 1971-72. Inland Waters Branch, DOE, Calgary.

Wetzel, R.G. 1965. Nutritional aspects of algal productivity in marl lakes with particular reference to enrichment bioassays and their interpretation. In: Primary productivity in aquatic environments. Univ. of California Press, Berkley, Calif., pp. 139-157.

__________. 1966. Productivity and nutrient relationships in marl lakes of Northern Indiana. Verh. Int. Ver. Limnol., 16: 321-332.

__________. 1968. Dissolved organic matter and phytoplankton productivity in marl lakes. Mitt. Int. Ver. Limnol., 14: 261-270.

__________. 1970. Recent and post-glacial production rates of a marl lake. Limnol. Oceanogr., 15: 491-503.

__________. 1972. The role of carbon in hard water marl lakes. In: ASLO Special Symposium, Vol. I, G.E. Likens ed., Allen Press, Lawrence, Kansas.

*Williams, D.J. 1972. The general limnology of the mainstem lakes in the Okanagan Valley, B.C. MS Report. Canada Centre for Inland Waters, 130p. plus Figs.

NOTE: References marked with an asterisk (*), were reports submitted to the Canada-British Columbia Okanagan Basin Study Committee in fulfilment of tasks funded under the Canada-British Columbia Okanagan Basin Agreement.